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Synthesis and Alkali-Metal-Ion Complexation of P-Stereogenic Diphosphacrowns

Yasuhiro Morisaki,^{*,[a]} Ryosuke Kato,^[b] and Yoshiki Chujo^{*,[b]}

Phosphine is conformationally stable because of the high inversion energy barrier of the phosphorus atom, which allows the phosphorus atom to become a chiral center. Thus, enantiopure P-stereogenic 12-, 15-, 18-, and 21-membered aliphatic phosphines "diphosphacrowns" were synthesized from secondary P-stereogenic bisphosphine as a chiral building block. Their complexation behaviors with alkali metal ions are investigated in comparison with benzo-18-diphosphacrown-6 and benzo-18-crown-6. 15-, 18-, and 21-Membered diphospha-

crowns captured alkali metal ions to form 1:1 metal complexes. Unique guest selectivity was observed, as diphosphacrowns encapsulated smaller alkali metal ions than common crown ethers; for example, 18-membered diphosphacrowns interacted more strongly with Na⁺ than K⁺. The difference in guest selectivity between diphosphacrowns and common crown ethers is speculated to result from the cavity size, owing to the large phosphorus atom as well as steric hindrance around the phosphine moiety.

1. Introduction

The first crown ether (dibenzo-18-crown-6) was reported by Pedersen in 1967^[1] and represents a host molecule that can encapsulates cationic guests such as alkali metal ions and ammonium.^[2] The guest selectivity of crown ethers can be controlled by the ring size, skeleton, and donor atoms. Since their discovery, a variety of crown ether derivatives have been synthesized. For example, various azacrown and thiocrown derivatives,^[3,4] which contain nitrogen and sulfur as donor atoms instead of oxygen, have been prepared. These derivatives exhibit unique guest-encapsulating abilities toward a variety of heavy metal ions in addition to alkali metal ions, and may have applications as heavy-metal ion sensors.

Phosphacrowns possessing trivalent phosphorus atoms as donor atoms have also been synthesized.^[5] Phosphine is conformationally stable because of the high inversion energy barrier of the phosphorus atom, which allows the phosphorus

atom to become a chiral center.^[6] We have developed practical synthetic routes to enantiopure P-stereogenic benzodiphosphacrowns^[7a] by using an optically active bisphosphine^[8] as a chiral element block.^[9] Phosphorus exhibits a high affinity towards transition metals, and phosphines can be used as ligands for transition-metal-catalyzed asymmetric reactions. Previously, we disclosed that diphosphacrowns could coordinate transition metals such as Pt^{II} and Pd^{II}; notably, the metals were captured outside of the ring.^[7a] However, the complexation of other metal ions has not been investigated. In this study, aliphatic diphosphacrowns (*R,R*)-**1b–e** with 12-, 15-, 18-, and 21-membered rings, respectively, were synthesized (Figure 1).^[7a] The complexation of alkali metal ions was investigated, in addition to that by benzo-18-diphosphacrown-6 (*R,R*)-**1a** (Figure 1).

2. Results and Discussion

2.1. Synthesis

Aliphatic diphosphacrowns with various ring sizes were synthesized by using a secondary bisphosphine (*S,S*)-2-BH₃, as shown in Scheme 1. The synthesis of the secondary bisphosphine was established by Crépy and Imamoto.^[8] The secondary phosphine proton of (*S,S*)-2-BH₃ is readily exchanged with Li through the reaction with alkyllithium reagents, owing to the electron-withdrawing character of coordinated boranes. The treatment of (*S,S*)-2-BH₃ with *n*BuLi afforded the dilithiated species, which could be reacted with electrophiles. Without isolation, ditosylates were added to the dilithiated species to obtain the enantiopure aliphatic diphosphacrown–borane complexes (*R,R*)-**1b–e**–BH₃ in moderate isolated yields. Their structures were confirmed by ¹H, ¹³C, and ³¹P NMR spectroscopy (Figures S1–S12 in the Supporting Information) as well as high-resolution mass spectrometry (HRMS). Furthermore, the

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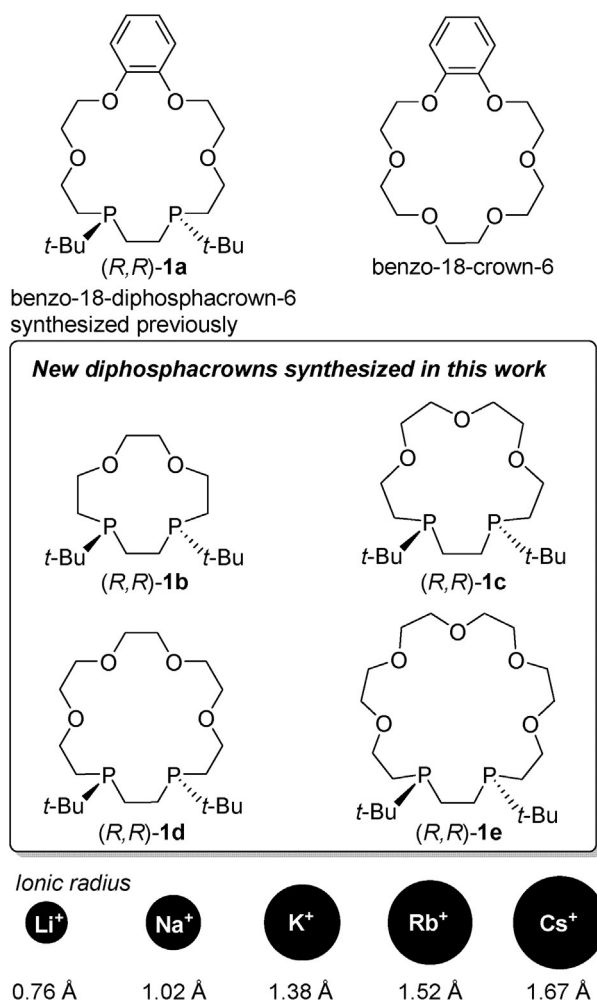
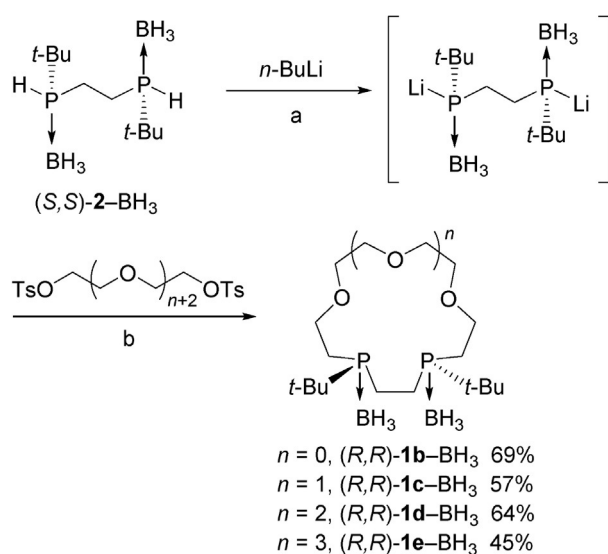


Figure 1. Structures of crown ethers used in this study and the ionic radii of alkali metal ions.



Scheme 1. Synthesis of diphosphacrowns (*R,R*)-1b-e-BH₃. Reagents and conditions: a) THF, -78 °C, 1 h; b) THF, from -78 °C for 1 h to rt for 48 h.

structures of (*R,R*)-1b-BH₃ and (*R,R*)-1c-BH₃ were confirmed by using X-ray crystallography (Figure 2 and Table S1).^[10] The single crystals were formed from CH₂Cl₂ and hexane (good and poor solvents, respectively), whereas suitable single crystals of (*R,R*)-1d-BH₃ and (*R,R*)-1e-BH₃ could not be obtained, because of the long and flexible oligo(ethyleneoxy) chains.

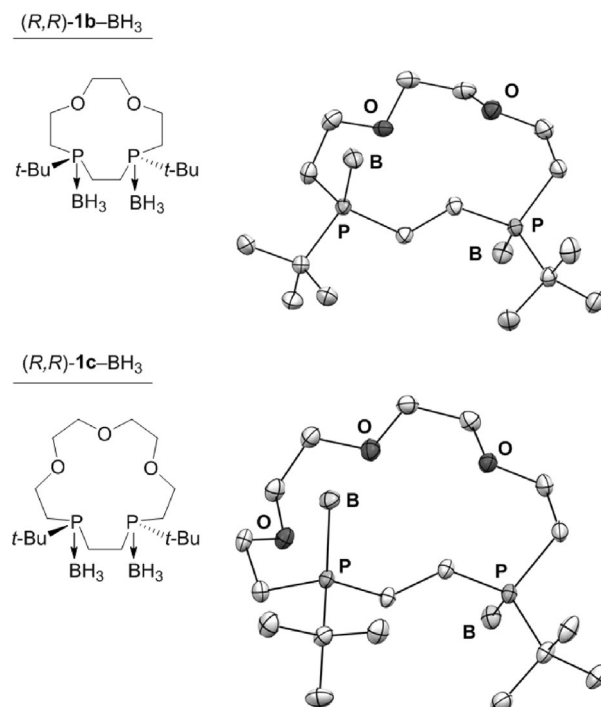


Figure 2. ORTEP drawings of (*R,R*)-1b-BH₃ and (*R,R*)-1c-BH₃. Thermal ellipsoids are drawn at the 50% probability level. Hydrogen atoms are omitted for clarity.

2.2. Complexation: Stoichiometry

The complexation behaviors of (*R,R*)-1a prepared previously^[7] and (*R,R*)-1b-e with five alkali metal ions (Li⁺, Na⁺, K⁺, Rb⁺, and Cs⁺, respectively) were examined. The removal of boranes from (*R,R*)-1a-e-BH₃ was carried out by adding excess CF₃SO₃H and successive treatment with KOH;^[11] the reaction conditions are shown in the Experimental Section. The complete removal of the boranes was confirmed by using ³¹P NMR spectra, as shown in Figure S13.

The complexation stoichiometry was determined by using Job plots and nonlinear curve fitting.^[12] Hexafluorophosphate salts (MPF₆; M = Li, Na, K, Rb, and Cs) were used. The association constants were estimated through titration by using ³¹P NMR spectroscopy, and the data are summarized in Table 1.

The complexation of alkali metal ions (Li⁺, Na⁺, and K⁺) with benzo-18-diphosphacrown-6 (*R,R*)-1a was evaluated by ³¹P NMR spectroscopy (³¹P NMR spectra for Job plots are shown in Figures S15-S17 and for titration are shown in Figures S18-S20). The Job plots are shown in Figures 3a-c; (*R,R*)-1a formed 1:1 complexes with Li⁺, Na⁺, and K⁺.

With 12-diphosphacrown-4 (*R,R*)-1b, no change in the chemical shifts of the ³¹P NMR spectra were observed upon addition

Table 1. Association constants for the 1:1 complexation of crown ethers with alkali metal ions.^[a]

Entry	Compound	Log <i>K</i> [$\Delta G^\circ/\text{kJmol}^{-1}$] ^[b]				
		Li ⁺	Na ⁺	K ⁺	Rb ⁺	Cs ⁺
1	benzo-18-diphosphacrown-6 (<i>R,R</i>)-1 a	1.50 (−8.42)	3.99 (−22.4)	2.37 (−13.3)		
2	12-diphosphacrown-4 (<i>R,R</i>)-1 b	–	–	–	–	–
3	15-diphosphacrown-5 (<i>R,R</i>)-1 c	1.65 (−9.26)	1.00 (−5.61)			
4	18-diphosphacrown-6 (<i>R,R</i>)-1 d	2.44 (−13.7)	4.53 (−25.4)	3.09 (−17.3)		
5	21-diphosphacrown-7 (<i>R,R</i>)-1 e	2.37 (−13.3)	3.44 (−19.3)	4.39 (−24.6)	4.23 (−23.7)	3.79 (−21.2)
6	benzo-18-crown-6 ^[c]	2.72 (−15.3)	3.72 (−20.9)	3.96 (−22.2)		

[a] Calculated by ³¹P NMR titration in CDCl₃/CD₃CN (v/v = 1/1) at 25 °C. [b] Calculated by ¹H NMR titration in CDCl₃/CD₃CN (v/v = 1/1) at 25 °C. [c] Standard free energy change.

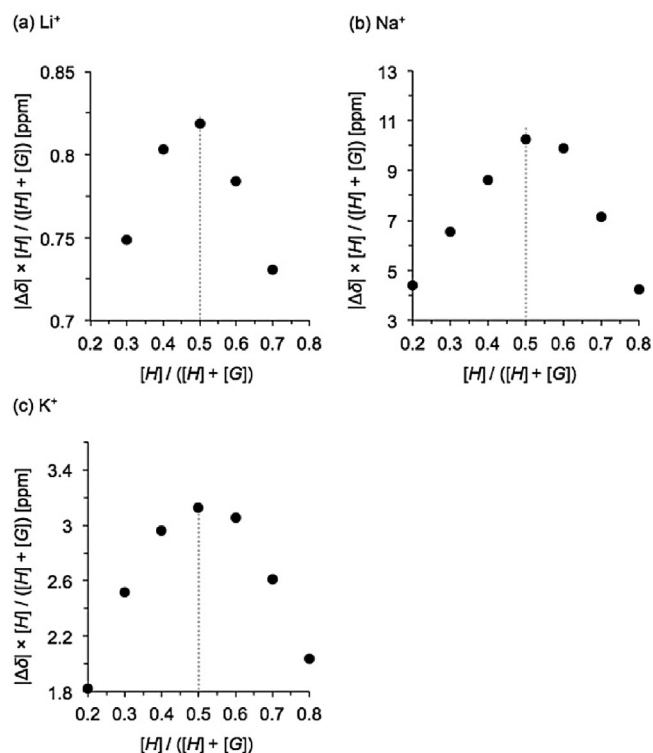


Figure 3. Job plots of (*R,R*)-1 **a** with Li⁺, Na⁺, and K⁺ in CDCl₃/CD₃CN (v/v = 1/1) at 25 °C; $\Delta\delta$, [H], and [G] denote change of chemical shift of phosphorus atom in (*R,R*)-1 **a**, total concentration of (*R,R*)-1 **a**, and total concentration of alkali metal ion M⁺, respectively. a) [H] + [G] = 2.19 × 10^{−2} M. b) [H] + [G] = 2.00 × 10^{−2} M. c) [H] + [G] = 2.36 × 10^{−2} M.

of alkali metal ions (Figure S14), suggesting that (*R,R*)-1 **b** did not form a complex with alkali metal ions. Generally, 12-crown-4 ring skeletons can capture small alkali metal ions such as Li⁺ and Na⁺.^[2] However, the 12-membered ring of (*R,R*)-1 **b** would be too small to encapsulate guest molecules even as small as Li⁺, owing to the bulky phosphine moieties.

Complexation of Li⁺ and Na⁺ by 15-membered ring (*R,R*)-1 **c** was observed in the ³¹P NMR spectra (³¹P NMR spectra for Job plots are shown in Figures S23 and S24 and for titration are shown in Figures S25 and S26). The Job plots and titration results are shown in Figures S27 and S28, respectively. The Job plots indicate that (*R,R*)-1 **c** could form 1:1 complexes with Li⁺ and Na⁺.

Diphosphacrown (*R,R*)-1 **d**, which has an 18-membered ring, could also capture alkali metal ions (Li⁺, Na⁺, and K⁺), as indicated by the corresponding Job plots (Figure S35 a–c, respectively). ³¹P NMR spectra for the Job plots are shown in Figures S29–S31 and for the titration are shown in Figures S32–S34.

21-Diphosphacrown-7 (*R,R*)-1 **e** formed 1:1 complexes with all alkali metal ions (Li⁺, Na⁺, K⁺, Rb⁺, and Cs⁺), as shown in Figure S47 a–e (³¹P NMR spectra for Job plots are shown in Figures S37–S41 and for the titration are shown in Figures S42–S46).

2.3. Complexation: Association Constant

The association constants (log *K*) of diphosphacrowns with alkali metal ions were calculated. In the case of (*R,R*)-1 **a**, log *K* values were estimated to be 1.50, 3.99, and 2.37 M^{−1}, as shown in Figure 4 a–c, respectively, and in entry 1 in Table 1. The selectivity followed the order Li⁺ < K⁺ < Na⁺; thus, (*R,R*)-1 **a** interacted with Na⁺ more strongly than K⁺.

The log *K* values for (*R,R*)-1 **c** were calculated to be 1.65 and 1.00 M^{−1}, respectively (Figure S28 and entry 3 in Table 1). Although the values were low, interaction with Li⁺ was preferred over that with Na⁺, despite the 15-membered crown ring.

The log *K* values of (*R,R*)-1 **d** with Li⁺, Na⁺, and K⁺ were calculated, and the values were 2.44, 4.53, and 3.09 M^{−1}, as shown in Figure S36 a–c, respectively, and in entry 4 in Table 1. The selectivity was identical to that of (*R,R*)-1 **a** (Li⁺ < K⁺ < Na⁺), whereas (*R,R*)-1 **d** and (*R,R*)-1 **a** encapsulated Na⁺ more strongly than K⁺.

The log *K* values of (*R,R*)-1 **e** were calculated to be 2.37, 3.44, 4.39, 4.23, and 3.79 M^{−1} (Figure S48 a–e, respectively, and entry 5 in Table 1).

For comparison, we selected benzo-18-crown-6 as a representative crown ether derivative, and the complexation behaviors with alkali metal ions (Li⁺, Na⁺, and K⁺) were examined under the same conditions. According to the titration results obtained by using ¹H NMR spectroscopy, the log *K* values with Li⁺, Na⁺, and K⁺ were calculated to be 2.72, 3.72, and 3.96 M^{−1} (Figure S49 and entry 6 in Table 1). As expected, the order of the selectivity was Li⁺ < Na⁺ < K⁺, which was in accord with previous reports.^[2a,b,13] Generally, 18-membered crown ether derivatives including heteroatom-containing crown ethers have strong affinities toward K⁺. For example, the log *K* values of benzo-18-crown-6 with Na⁺ and K⁺ in Me₂SO at 25 °C were

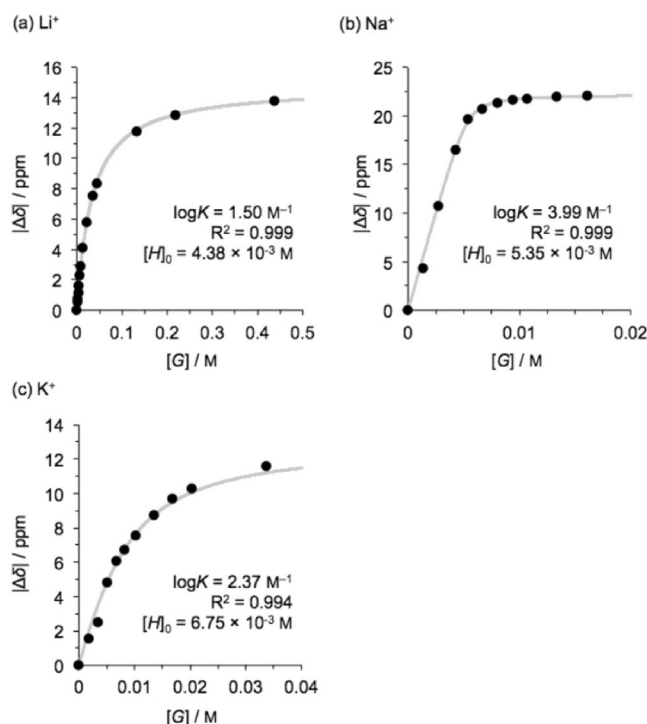


Figure 4. ^{31}P NMR titration of (R,R) -1a with Li^+ , Na^+ , and K^+ in $\text{CDCl}_3/\text{CD}_3\text{CN}$ ($v/v = 1/1$) at room temperature; $\Delta\delta$ and $[G]$ denote change of chemical shift of phosphorus atom in (R,R) -1a and total concentration of the added alkali metal ion M^+ , respectively. Total concentration of (R,R) -1a $[H]_0$ is constant.

estimated to be 1.70 and 2.85 M^{-1} , respectively,^[13a] and those in MeOH at 25°C were estimated to be 4.03 and 5.27 M^{-1} , respectively.^[13b] The difference in guest selectivity between diphosphacrowns and common crown ethers is speculated to result from the cavity size as well as steric hindrance around the phosphorus atom. Although a carbon–phosphorus single bond (1.83 \AA) is longer than carbon–oxygen single bond (1.50 \AA), the atomic radius of the phosphorus atom (0.98 \AA) is much larger than that of the oxygen atom (0.48 \AA); thus, the cavity size of a diphosphacrown is smaller than that of a common crown ether. Cavity sizes of 18-diphosphacrown-6 and 18-crown-6 were estimated by the cavity area, on the assumption that all atoms in the ring skeleton are on the same plane, as shown in Figure S50.

2.4. Guest-Exchange Study

The guest-exchange behaviors of (R,R) -1a were monitored by using ^{31}P NMR spectra, as shown in Figure 5. Addition of three equivalents of Na^+ to the (R,R) -1a- K^+ complex solution led to complete guest exchange, owing to the larger K value of complexation with Na^+ [$\log K(\text{Na}^+) = 3.99$] compared to K^+ [$\log K(\text{K}^+) = 2.37$] (entry 1 in Table 1). The signal at -11.1 ppm disappeared, and a new signal was observed at -22.5 ppm . On the other hand, when four equivalent free benzo-18-crown-6 moieties were added to (R,R) -1a- K^+ complex solution, K^+ was moved to benzo-18-crown-6, which has a larger K value [$\log K(\text{K}^+) = 3.96$, entry 5 in Table 1] than (R,R) -1a [\log

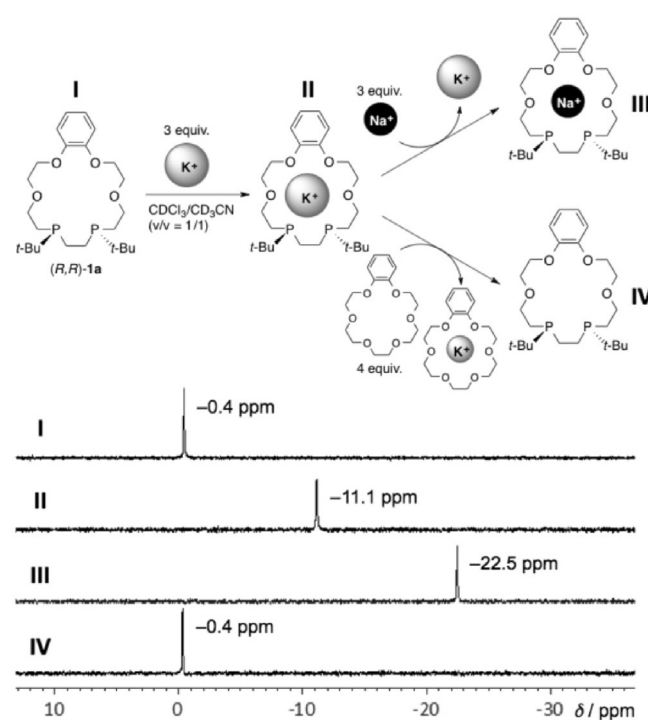


Figure 5. Guest-exchange reactions of (R,R) -1a with three equivalents of K^+ (from I to II), (R,R) -1a- K^+ with three equivalents of Na^+ (from II to III), and (R,R) -1a- K^+ with four equivalents of benzo-18-crown-6 (from II to IV). ^{31}P NMR spectrum in $\text{CDCl}_3/\text{CD}_3\text{CN}$ ($v/v = 1/1$) of each stage.

$K(\text{K}^+) = 2.37$, entry 1 in Table 1]. Thus, the signal at -11.1 ppm was shifted to -0.4 ppm , which was the identical chemical shift of free bisphosphine in (R,R) -1a.

The association constants of aliphatic diphosphacrown (R,R) -1d with alkali metals were larger than those of benzodiphosphacrown (R,R) -1a; for example, the $\log K(\text{Na}^+)$ value of (R,R) -1d was 4.53 M^{-1} , whereas that of (R,R) -1a was 3.99 M^{-1} . Therefore, the relative encapsulating selectivity among Li^+ , Na^+ , and K^+ was examined. $K(\text{Na}^+)/K(\text{K}^+)$ and $K(\text{K}^+)/K(\text{Li}^+)$ of (R,R) -1d were 27.2 and 4.5 , respectively, whereas $K(\text{Na}^+)/K(\text{K}^+)$ and $K(\text{K}^+)/K(\text{Li}^+)$ of (R,R) -1a were 32.1 and 7.3 , respectively. Thus, the relative encapsulating selectivity of the benzodiphosphacrown was higher than that of the aliphatic diphosphacrown. Aliphatic diphosphacrowns have flexible ethyleneoxy chains, resulting in larger encapsulating abilities and lower encapsulating selectivities than benzodiphosphacrowns.

3. Conclusions

P-Stereogenic 12-, 15-, 18-, and 21-membered diphosphacrowns were synthesized from secondary P-stereogenic bisphosphine as a chiral building block. 15-, 18-, and 21-Membered diphosphacrowns captured alkali metal ions, and the corresponding Job plots indicated the formation of 1:1 metal complexes. Notably, unique guest selectivity was observed, as diphosphacrowns encapsulated smaller alkali metal ions than common crown ethers. For example, 18-membered diphosphacrowns interacted more strongly with Na^+ than K^+ . The relative encapsulating selectivity of the benzodiphosphacrown

was greater than that of aliphatic diphosphacrown, owing to the phosphorus atom being larger than oxygen as well as the steric hindrance around the phosphorus atom. The flexible ethyleneoxy chain of the aliphatic diphosphacrowns resulted in a larger encapsulating ability and lower encapsulating selectivity than the rigid phenylene skeleton of the benzodiphosphacrown.

Experimental Section

General

^1H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded on a JEOL JNM-EX400 spectrometer, and samples were analyzed in CD_3CN or CDCl_3 by using Me_4Si as an internal standard. ^{31}P (161.9 MHz) NMR spectra were also recorded on a JEOL JNM-EX400 spectrometer, and samples were analyzed in CD_3CN or CDCl_3 by using H_3PO_4 as an external standard. The following abbreviations are used; s: singlet, d: doublet, t: triplet, q: quartet, m: multiplet, and br: broad. HRMS spectra were obtained on a Thermo Fisher Scientific EXACTIVE for electron-spray ionization (ESI). Optical rotations were measured on a Rudolph Research Analytical AUTOPOL IV instrument by using CHCl_3 as a solvent. Analytical thin-layer chromatography was performed with SiO_2 60 Merck F_{254} plates. Column chromatography was performed with Wakogel C-300 SiO_2 or MERCK Al_2O_3 90 active basic.

Materials

THF and Et_2O were purchased and purified by the GlassContour solvent purification system.^[14] Dehydrated-grade toluene and EtOH were purchased and used without further purification. Bisphosphine (*S,S*)-2-BH₃ was synthesized following the method described in the literature.^[8] The other materials were purchased and used without further purification. Alkali metal salts RbPF_6 and CsPF_6 were prepared by using the procedure in the literature.^[15] All reactions were performed under an Ar atmosphere using standard Schlenk techniques.

Synthesis of P-Stereogenic Diphosphacrowns

A typical procedure is as follows. A THF solution (30 mL) of (*S,S*)-2-BH₃ (117.0 mg, 0.50 mmol) was cooled to -78°C under an Ar atmosphere. To this solution, *n*BuLi (1.6 M in *n*-hexane, 0.75 mL, 1.2 mmol) was added with a syringe. After stirring for 1 h, a THF solution (20 mL) of triethylene glycol ditosylate (229.3 mg, 0.50 mmol) was added with a syringe. The reaction mixture was allowed to warm to room temperature. After stirring for 48 h, the reaction was quenched upon addition of H_2O (30 mL). The organic layer was extracted with EtOAc (50 mL \times 3). The combined organic layers were washed with brine and dried over MgSO_4 . After filtration, the solvent was removed in vacuo. The residue was subjected to column chromatography on SiO_2 with EtOAc and hexane (*v/v* = 2/1) as an eluent. The solvent was removed in vacuo to afford (*R,R*)-1 b-BH₃ (120.4 mg, 0.35 mmol, 69%) as a colorless solid.

(*R,R*)-1 b-BH₃: R_f = 0.8 (EtOAc and hexane, *v/v* = 1/2); $[\alpha]_D^{21} = -4.3$ (*c* = 0.5 in CHCl_3); ^1H NMR (CDCl_3 , 400 MHz) δ = 0.34 (br q, $J_{\text{H-B}}$ = 106.4 Hz, 6H), 1.15 (d, J = 13.2 Hz, 18H), 1.63–1.71 (m, 2H), 1.74–1.85 (m, 2H), 1.96–2.07 (m, 2H), 2.52–2.62 (m, 2H), 3.55 (s, 4H), 3.74–3.93 ppm (m, 4H); ^{13}C NMR (CDCl_3 , 100 MHz) δ = 15.4 (d, $J_{\text{C-P}}$ = 31.5 Hz), 22.1 (d, $J_{\text{C-P}}$ = 32.1 Hz), 25.1, 28.3 (d, $J_{\text{C-P}}$ = 34.8 Hz),

65.7, 70.2 ppm; $^{31}\text{P}\{^1\text{H}\}$ NMR (CDCl_3 , 161.5 MHz) δ = +35.5 ppm (br d, $J_{\text{P-B}}$ = 64.5 Hz); HRMS (ESI) calcd for $[\text{C}_{16}\text{H}_{40}\text{B}_2\text{O}_5\text{P}_2+\text{NH}_4]^+$ 366.3028, found 366.3025.

(*R,R*)-1 c-BH₃: Yield 57% (112.4 mg, 0.29 mmol), colorless solid; R_f = 0.5 (EtOAc and hexane, *v/v* = 1/1); $[\alpha]_D^{21} = +8.1$ (*c* = 0.5 in CHCl_3); ^1H NMR (CDCl_3 , 400 MHz) δ = 0.37 (br q, $J_{\text{H-B}}$ = 110.9 Hz, 6H), 1.17 (d, J = 13.6 Hz, 18H), 1.80–2.17 (m, 8H), 3.58–3.93 ppm (m, 12H); ^{13}C NMR (CDCl_3 , 100 MHz) δ = 15.2 (d, $J_{\text{C-P}}$ = 30.2 Hz), 21.6 (d, $J_{\text{C-P}}$ = 31.2 Hz), 25.3, 28.6 (d, $J_{\text{C-P}}$ = 33.9 Hz), 66.4, 70.3, 71.3 ppm; $^{31}\text{P}\{^1\text{H}\}$ NMR (CDCl_3 , 161.5 MHz) δ = +32.6 ppm (d, $J_{\text{P-B}}$ = 63.8 Hz); HRMS (ESI) calcd for $[\text{C}_{18}\text{H}_{44}\text{B}_2\text{O}_5\text{P}_2+\text{NH}_4]^+$ 410.3290, found 410.3283.

(*R,R*)-1 d-BH₃: Yield 64% (140.3 mg, 0.32 mmol), colorless solid; R_f = 0.13 (EtOAc and hexane, *v/v* = 1/1); $[\alpha]_D^{23} = +10.5$ (*c* = 0.5, CHCl_3); ^1H NMR (CDCl_3 , 400 MHz) δ = 0.35 (br q, $J_{\text{H-B}}$ = 116.0 Hz, 6H), 1.17 (d, J = 13.4 Hz, 18H), 1.85–2.02 (m, 8H), 3.59–3.81 ppm (m, 16H); ^{13}C NMR (CDCl_3 , 100 MHz) δ = 15.2 (d, $J_{\text{C-P}}$ = 30.4 Hz), 21.3 (d, $J_{\text{C-P}}$ = 30.8 Hz), 25.3, 28.5 (d, $J_{\text{C-P}}$ = 34.1 Hz), 66.3, 70.4, 70.5, 70.9 ppm; $^{31}\text{P}\{^1\text{H}\}$ NMR (CDCl_3 , 161.5 MHz) δ = +32.1 ppm (br d, $J_{\text{P-B}}$ = 54.9 Hz); HRMS (ESI) calcd for $[\text{C}_{20}\text{H}_{48}\text{B}_2\text{O}_5\text{P}_2+\text{Na}]^+$ 459.3106, found 459.3087.

(*R,R*)-1 e-BH₃: Yield 45% (107.8 mg, 0.22 mmol), colorless liquid; R_f = 0.05 (EtOAc and hexane, *v/v* = 1/1); $[\alpha]_D^{21} = +3.0$ (*c* = 0.25 in CHCl_3); ^1H NMR (CDCl_3 , 400 MHz) δ = 0.35 (br q, $J_{\text{H-B}}$ = 56.8 Hz, 6H), 1.17 (d, J = 13.6 Hz, 18H), 1.86–2.02 (m, 8H), 3.59–3.78 ppm (m, 20H); ^{13}C NMR (CDCl_3 , 100 MHz) δ = 15.2 (d, $J_{\text{C-P}}$ = 30.8 Hz), 21.2 (d, $J_{\text{C-P}}$ = 30.8 Hz), 25.2, 28.4 (d, $J_{\text{C-P}}$ = 33.7 Hz), 66.1, 70.1, 70.2, 70.4, 70.6 ppm; $^{31}\text{P}\{^1\text{H}\}$ NMR (CDCl_3 , 161.9 MHz) δ = +33.1 ppm (d, $J_{\text{P-B}}$ = 44.6 Hz); HRMS (ESI) calcd for $[\text{C}_{22}\text{H}_{52}\text{B}_2\text{O}_5\text{P}_2+\text{NH}_4]^+$ 498.3814, found 498.3815.

Removal of Borane from Diphosphacrown

All sample preparation procedures were performed under an Ar atmosphere. To a solution of (*R,R*)-1-BH₃ (0.10 mmol) in degassed dry toluene (0.5 mL), $\text{CF}_3\text{SO}_3\text{H}$ acid (0.5 mL, 6 mmol) was added through a syringe. After stirring for 2 h at room temperature, toluene was removed in vacuo. The residue was dissolved in degassed EtOH (3 mL) and added to degassed KOH aqueous solution (1.1 g, 20 mmol KOH in 20 mL H_2O). After stirring for 5 h at 50°C , the solution was allowed to cool to room temperature. Then, extraction with degassed Et_2O was carried out. The organic layer was dried over MgSO_4 and purified with column chromatography on Al_2O_3 (active basic) to obtain (*R,R*)-1 as a colorless solid.

Determination of Stoichiometry by Job Plot

The “total concentration of (*R,R*)-1 and MPF_6 ” and the “solvent ratio ($\text{CDCl}_3/\text{CD}_3\text{CN}$, *v/v* = 1/1)” were both constant, and (*R,R*)-1 in CDCl_3 solution and MPF_6 in CD_3CN solution were added to a NMR tube at various ratios. In each case, the ^1H NMR and ^{31}P NMR spectra were monitored, and the data were analyzed by using the Job plot method. The stoichiometry was obtained from the *x* coordinate at the maximum in the Job plot curve. In this case, the *y* axis is $|\Delta\delta| \cdot [H]/([H] + [G])$; $|\Delta\delta|$ = absolute value of chemical shift variation upon complexation, $[H]$ = concentration of (*R,R*)-1, and $[G]$ = concentration of MPF_6 . The *x* axis is the mole fraction of (*R,R*)-1, $[H]/([H] + [G])$. For *x* = 0.5, the stoichiometry of the binding is 1:1.

Determination of Association Constants

Determination of the association constants for the (*R,R*)-1-MPF₆ complexes was carried out by means of an NMR titration technique in CDCl₃/CD₃CN (*v/v* = 1/1) at 25 °C. The concentration of (*R,R*)-1, [H]₀, in CDCl₃ was kept constant, while the concentration of MPF₆, [G], in CD₃CN was varied. These two solutions were mixed, and ¹H and ³¹P NMR spectra were recorded. The host–guest complexation equilibrium has a sufficiently fast exchange rate compared to the NMR timescale, showing only one set of resonances for the ligand protons and phosphorus. The association constants were determined through nonlinear curve-fitting analysis with complexation-induced downfield or upfield shifting of the data for the host protons upon the addition of a guest. In this case, the association constants calculated individually from the chemical shift variation of protons and phosphorus were almost identical; therefore, all binding constants were calculated from the data of ³¹P NMR spectra. The *y* axis is |Δδ|, and the *x*-axis is [G]. The association constant *K* and |Δδ_{max}| were calculated from Equation (1) by using nonlinear curve fitting:

$$|\Delta\delta| = \frac{|\Delta\delta_{\max}| \{1 + K[G] + K[H]_0 - [(1 + K[H]_0 + K[G])^2 - 4K^2[G][H]_0]^{0.5}\}}{2K[H]_0} \quad (1)$$

Guest-Exchange Study

A stock solution of (*R,R*)-1 **a** (1.6 × 10^{−2} M) in CDCl₃/CD₃CN (*v/v* = 1/1) was prepared, and a ³¹P NMR spectrum was recorded (state I). Then, three equivalents of KPF₆ were added to the solution, and the ³¹P NMR spectrum was subsequently recorded (state II). To the stock solution containing (*R,R*)-1 **a** and KPF₆, NaPF₆ [3 equiv against (*R,R*)-1 **a**] was added, and the ³¹P NMR spectrum was again recorded (state III). In addition, to the stock solution containing (*R,R*)-1 **a** and KPF₆, benzo-18-crown-6 [4 equiv against (*R,R*)-1 **a**] was added, and the final ³¹P NMR spectrum was recorded (state IV).

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